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Local measurements and a new flow pattern based model for subcooled and saturated flow boiling heat transfer in multi-microchannel evaporators

Houxue Huang [*], John R. Thome

Laboratory of Heat and Mass Transfer, École Polytechnique Fédérale de Lausanne, EPFL-STI-IGM-LTCM, Station 9, CH-1015 Lausanne, Switzerland

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ABSTRACT

A comprehensive experimental campaign has been conducted to measure the local heat transfer coefficients during flow boiling of refrigerants in multi-microchannel evaporators. Two additional refrigerants (R245fa and R236fa) were tested in two silicon evaporators at three inlet subcoolings and at three outlet saturation temperatures. The test section backside temperatures were measured by a fine-resolution infrared (IR) camera providing a two-dimensional thermal map, which was used by solving the three-dimensional inverse heat conduction problem to obtain the local heat transfer coefficients on a pixel-by-pixel basis. The experimental results revealed different trends along the flow direction. The decreasing trend (when existing) at the beginning of the channel was attributable to the single-phase thermal developing flow, then heat transfer increased from the onset of subcooled flow boiling up until the onset of saturated flow boiling, and afterwards it decreased again until entering the annular flow regime where it started to pick up and rose significantly. Combining our new data together with our recent experimental work of Huang et al. (2016), a new flow pattern based model has been proposed for local heat transfer prediction, starting from single-phase flow all the way through to annular flow. This new model also included a new local heat transfer method for the subcooled flow boiling region since no truly local subcooled heat transfer prediction method can be found in the literature for microchannels. This new flow pattern based model predicted the total local heat transfer database (1,941,538 local points) well with a MAE of 14.2% and with 90.1% of the data predicted within ±30%. It successfully tracks the experimental trends without any jumps in predictions when changing flow patterns.

1. Introduction

Flow boiling heat transfer in multi-microchannel evaporators has been of interest to both industry and academia for more than a decade [2–6]. However, the dominating heat transfer mechanisms with respect to governing flow boiling in multi-microchannel evaporators has been debatable over the role of nucleate boiling in the low vapor quality region [6–9,1]. With respect to flow boiling in macrochannels, the numerous small bubbles growing at the wall in the low quality region are not confined by the channel wall, and hence it is generally thought that nucleate boiling plays an important role, while in the high vapor quality region convective flow boiling takes over. However, when the channel size is reduced to the micro-scale ($Co > 0.5$), the bubbles are subject to the confinement of the channel wall [3]. In this case, directly extrapolating the heat transfer mechanisms occurring in macrochannels to explain what is happening in microchannels is questionable.

A recent study by Huang et al. [1] has shed a little more light on these pertinent heat transfer mechanisms. In that study, a new environmentally friendly refrigerant R1233zd(E) was tested as the working fluid while in the present study new data are obtained for R245fa and R236fa. Their fine-resolution local heat transfer coefficients were obtained through solving the 3D inverse heat conduction problem with a 2D temperature map recorded by an infrared (IR) camera as the input condition [10]. The fine-resolution local heat transfer data in the saturated flow boiling region were compared with existing heat transfer models. The mechanistic flow pattern based model by Costa-Patry and Thome [9] combining the three-zone model of Thome et al. [6] for low vapor qualities and the annular flow model of Cioncolini and Thome [7] for medium and high vapor qualities showed the best agreement with the experimental data. Therefore, the thin liquid

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[*] Corresponding author.
E-mail addresses: houxue.huang@epfl.ch, houxue.huang@gmail.com (H. Huang).

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Nomenclature

Roman	Description
A	cross section area (m^2)
ar	aspect ratio (–)
Bo	boiling number (–)
$C_1 - C_4$	empirical coefficient (–)
Co	confinement number (–)
c_p	heat capacity ($\mathrm{J\,kg^{-1}\,K^{-1}}$
D_h	hydraulic diameter (m)
f	fanning factor (–)
G	mass flux ($\mathrm{kg\,m^{-2}\,s^{-1}}$)
H_{lv}	latent heat of vaporization ($\mathrm{J\,kg^{-1}}$)
Ja^*	modified Jacob number (–) $Ja^* = \frac{c_{p,l}\Delta T_{sub,inlet}}{H_{lv}}$
k	thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
L	length (m)
m	fin parameter ($\mathrm{m^{-1}}$)) and coefficient
$\dot{m}$	total mass flowrate ($\mathrm{kg\,s^{-1}}$)
$\dot{m}_0$	mass flowrate at each calculated channel ($\mathrm{kg\,s^{-1}}$), $\dot{m}_0 = \dot{m}/N$
N	microchannel number (–)
Nu	Nusselt number (–)
Pr	Prandtl number (–), $Pr = \frac{c_p\mu}{k}$
Q	heat transfer rate (W)
q	heat flux ($\mathrm{W\,m^{-2}}$)
Re	Reynolds number (–), $Re = \frac{GD_h}{\mu}$
r	ratio (–)
T	temperature (K)
UWH	uniform wall heat flux (–)
UWT	uniform wall temperature (–)
W	width (m)
We^*	modified Webber number (–), $We^* = \frac{G^2 D_h}{(\rho_l - \rho_v)\sigma}$
X_{tt}	Lockhart–Martinelli parameter of turbulent liquid–turbulent vapor flows (–)
x	dimension in thickness direction (m) and vapor quality (–)
y	dimension in widthwise direction (m)
z	dimension in lengthwise direction (m)
z^*	dimensionless length (–)
Greek α	heat transfer coefficient ($\mathrm{W\,m^{-2}\,K^{-1}}$)
Δ	difference (–)
γ	coefficient (–)
μ	viscosity ($\mathrm{Pa\,s^{-1}}$)
σ	surface tension ($\mathrm{N\,m^{-1}}$)
Subscripts $3Z$	three zone
AF	annular flow
amb	ambient
$axial$	axial heat conduction
b	bottom
$base$	test section base
$CB - AF$	coalescing bubble to annular flow regime
ch	channel
Exp	experiment
e	east
eff	effective
FC	forced convection
f	fin
ftp	footprint
$inlet$	inlet
IR	IR camera
l	liquid
lo	liquid only
loc	local
$long$	long edge
$loss$	total heat loss
mf	manifold
ME	microchannel evaporator
MY	Muzychka and Yovanovich
n	north
$Pred$	prediction
s	south
$short$	short edge
sp	single-phase
t	top
$total$	total
v	vapor
vo	vapor only
w	west
$wall$	channel wall
$wire$	electrical power wires

film evaporation process of the three-zone model was concluded to be the dominant mechanism controlling saturated flow boiling heat transfer in slug flow in microchannels rather than nucleate boiling.

In two-phase cooling of electronics, the fluid is preferred to enter the microchannel evaporators with an inlet subcooling to reduce the inlet restriction pressure drop and to avoid flow boiling instabilities. When a subcooled fluid flows through a sufficiently heated channel, it usually first experiences a single-phase liquid region and/or a subcooled flow boiling region, and finally a saturated flow boiling region, as schematically demonstrated in Fig. 1. The length of each segment depends on the specific experimental conditions, such as the inlet subcooling, mass flux, heat flux and wall superheat, etc.

However, compared to saturated flow boiling, the number of studies on the subcooled flow boiling in microchannel evaporators is limited [11–15], and thereby there are few local subcooled flow boiling heat transfer data available.

Liu and Garimella [14] studied the flow boiling heat transfer of water in two microchannel evaporators considering the heat transfer in single-phase, subcooled and saturated flow boiling regions. The length of the subcooled flow boiling region was identified by using their own model for the onset of nucleate boiling (ONB) developed in [13]. The local wall temperature was extrapolated based on three thermocouples (with an interval of 1.02 cm) placed at a distance of 3.17 mm to the microchannel base. A length averaged heat transfer coefficient between the single-phase and subcooled flow boiling region was compared with conventional correlations, where the Shah correlation [16] was shown to be accurate for the prediction.

Lee and Mudawar [15] investigated subcooled flow boiling heat transfer of HFE7100 in microchannel heat sinks. The subcooled flow boiling heat transfer methods developed for macrochannels were proven to be unsuitable to predict their microchannel data. Therefore, new empirical models for the incipient heat flux and the mean subcooled flow boiling heat transfer were proposed, which provided good agreement with their experimental data. Later, this model was used by Kim and Mudawar [17] for the heat transfer prediction in the subcooled flow boiling region. Thereby, averaged heat transfer coefficients versus the vapor quality at the channel outlet were reported.